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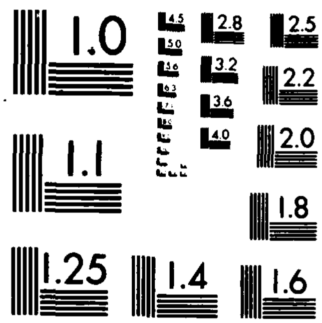

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MELBOURNE, VICTORIA

Aerodynamics Technical Memorandum 377

HELICOPTER HOVER PERFORMANCE ESTIMATION COMPARISON WITH UH-IH IROQUOIS FLIGHT DATA

by

M.J. WILLIAMS and A.M. ARNEY

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M.J. WILLIAMS and A.M. ARNEY

SUMMARY

The hover performance of the UH-1H Iroquois has been estimated under a variety of operational conditions using POLAR2, a program based on blade element theory. This program is an improved version of POLAR, a program previously developed at ARL, which did not allow for compressibility effects. The occurrence of these effects in a hovering situation is discussed, and a relationship allowing for such effects has been derived and included in POLAR2. Other improvements, designed to make the program more convenient to use include the calculation of tail rotor performance together with variables such as tip loss, air density and Lock number which were previously input. The role of the induced velocity factor is also discussed. Finally, comparisons of estimates using POLAR2 and ARDU flight trials data for the UH-1H are presented.

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CONTENTS

NOTATION

B	tip loss factor
C_P	power coefficient, $P/\rho\pi R^2(\Omega R)^3$
C_T	thrust coefficient, $T/\rho\pi R^2(\Omega R)^2$
F_{blk}	fin blockage factor
I	blade mass moment of inertia about flapping hinge
M_o	blade tip Mach number at compressibility onset
M_{tip}	blade tip Mach number
ΔM	$M_{tip} - M_o$
N2	gas generator angular velocity (rpm)
P	power
Q	torque absorbed by main rotor, P/Ω
R	main rotor radius
T	rotor thrust
$(T_{TR})_{NET}$	net tail rotor anti-torque thrust required to balance main rotor torque
Z	main rotor height above ground
a	blade section lift curve slope
b	number of main rotor blades
c	blade section chord
k_h	induced velocity factor at hover
k_{ind}	induced velocity factor, $(P_i)_{actual}/(P_i)_{momentum}$
l_{TR}	distance of tail rotor from main rotor shaft
Ω	angular velocity of main rotor
$\alpha_{(1,270)}$	angle of attack of main rotor retreating blade at tip
γ	Lock number, $\rho acR^4/I$
μ	advance ratio
ν	induced velocity at rotor
ρ	density of air
σ	blade solidity; ratio of blade area to rotor disk area, $= bc/\pi R$

Subscripts

acc	accessories and transmission
c	compressibility
i	induced
o	profile
SL,ISA	sea level, ISA conditions
stall	stall
MR	main rotor
TR	tail rotor
∞	out of ground effect

GLOSSARY

ABS-RW	Aircraft Behaviour Studies - Rotary Wing
ARDU	Aircraft Research and Development Unit
ARL	Aeronautical Research Laboratories
AUW	All Up Weight
DPTV	Data Plate Torque Value
IGE	In Ground Effect
ISA	International Standard Atmosphere
OAT	Outside Air Temperature
OGE	Out of Ground Effect
PNG	Papua New Guinea
RAAF	Royal Australian Air Force
RAN	Royal Australian Navy
rpm	Revolutions Per Minute
RSRA	Rotor Systems Research Aircraft

1. INTRODUCTION

The hovering performance of the UH-1H Iroquois helicopter has been described in References 1, 2. Flight testing was carried out by ARDU for a wide range of operating conditions in Australia, PNG and Irian Jaya at density altitudes up to 12000 ft. Power consumption was derived from torque meter readings which were converted for presentation in nondimensional form, C_P vs C_T. Data were obtained OGE and IGE at a skid height of 3 ft with a view to formulating procedures for estimating power margins required over and above IGE values.

Following these tests a simple calculator was developed by ARDU for Service use, from which torque requirements for flight under varying conditions could be obtained rapidly. Later tests by Mackerras[3] under similar conditions confirmed the accuracy of the ARDU Performance Computer.

More recently the ABS-RW Group at ARL has been involved in performance estimation as part of tender evaluations of prospective helicopter acquisition by the RAN and RAAF. A simple program 'POLAR' has been described by Arney[4] which is based on blade element theory but makes no allowance for compressibility or stall effects. However, an indication of the likelihood of stall is output so that a manually applied correction may be made to the calculated profile power.

Comparison of 'POLAR' with flight results has shown good agreement at low thrust coefficients but underestimates at high thrust coefficients. For this reason the program prediction of torque margins compared with those given in Reference 3 is in error at the higher altitudes and AUW (high C_T).

The purpose of this Memo is to show results produced by an improved program 'POLAR2' which corrects these deficiencies. In the next section evidence of compressibility effects is noted in the flight data and the derivation of a simple expression to account for this

additional power loss is discussed. Other improvements incorporated in POLAR2 are discussed in the next section. Finally, predictions of POLAR2 are compared with flight data for hovering both OGE and IGE for a wide range of loadings and atmospheric conditions.

2. COMPRESSIBILITY EFFECTS AT HOVER

Examples of flight data from the ARDU reports [1,2] are reproduced in Figures 1a, b for the OGE, IGE cases respectively. Due to the difficulty of performing hover tests there is a fair degree of experimental scatter. The 'pessimism' curves represent the upper limit of the data i.e. maximum power likely for a given thrust. On the other hand, the mean curves were fitted and used by ARDU to form the basis of the ARDU Performance Calculators, especially prepared for engines of DPTV from 58 through 64.

Figure 2 shows a comparison of POLAR with the mean curve fitted to the flight data of Figure 1a. Like many performance programs POLAR requires an empirically based value of the induced velocity factor, k_{ind}, which is used to modify the induced velocity as given by momentum theory. In this manner, the induced power losses arising from 'non-ideal' inflow conditions are approximated. As described in Reference 4, POLAR set k_{ind} equal to 1.30 for any hovering helicopter. Figure 2 shows that by adjusting POLAR to use a value of $k_{ind} = 1.22$, good agreement can be obtained at conditions of low thrust and power coefficients, where stall and compressibility effects would be expected to be negligible. Further comment on the use of k_{ind} is given in the next section. As can be seen in Figure 2, with $k_{ind} = 1.22$, the estimate of power coefficient becomes progressively worse as thrust coefficient is increased. The additional power increment evidenced by flight data suggests the presence of compressibility effects, as blade angles of attack are well below stall.

Keys[5] presents data for the hover situation (reproduced here in Figure 3a) which gives the power increment arising from compressibility

as a function of C_T/σ (average angle of attack) and tip Mach number. Figure 3a shows a comparison between results given by vortex theory and CH-47 test data. The latter show a delayed M_{tip} effect which is ascribed to the relief afforded by three-dimensional flow at the blade tips. Reference 5 suggests that the experimental data should be applicable to other blades of thickness ratio in the 10-12% range, therefore an approximation to these compressibility power increments has been derived for use with POLAR2 as is shown in Figure 3b.

In the case of the two-bladed UH-1H main rotor, the tip speed is higher than most multi-bladed helicopters. An indication of the range of tip Mach number experienced during the ARDU flight tests is given in Table 1 below.

TABLE 1

Effect of atmospheric conditions on tip Mach number for rotor speeds used in UH-1H tests (References 1, 2)

Atmospheric Conditions			Tip Mach Number	
Altitude	O.A.T (°C)	Speed of Sound (ft/s)	N_2 = 6400 rpm RRPM = 315 ΩR = 791.7 ft/s	N_2 = 6600 rpm RRPM = 325 ΩR = 816.4 ft/s
ISA				
Sea Level	15	1116.4	0.709	0.731
5,000 ft	5	1097.1	0.722	0.744
10,000 ft	-5	1077.4	0.735	0.758
ARDU tropical atmosphere				
Sea Level	28	1114.1	0.694	0.716
5,000 ft	18	1122.7	0.705	0.721
10,000 ft	9	1104.1	0.717	0.740

From Table 1 it may be seen that under many flight conditions the tip Mach number exceeds M_o, the onset Mach number, as given by Figure 3b (top curve). For the flight data of Figure 1a, C_T/σ varies between 0.05 and 0.08 corresponding to an M_o variation from 0.72-0.68.

The effect of OAT, inasmuch as it influences M_{tip} is summarised in Figure 4. The solid lines are power vs thrust curves for the UH-1H obtained for different but constant OATs. Compressibility effects alone account for the divergence of the curves. Also indicated is the locus taken for constant AUW and varying altitude for an ISA+5°C atmosphere. A rapidly increasing power increment is shown as M_{tip} rises with decreasing temperature at higher altitudes.

3. PERFORMANCE PREDICTION PROGRAM - POLAR2

The main deficiency of the earlier program POLAR has been *rectified in POLAR2 by the addition of a profile power compressiblity* factor based on the data of Reference 5. This was fully discussed in Section 2. Before demonstrating its effect on predicted performance, several other improvements which have been included in POLAR2 are discussed below.

3.1 Blade Tip Loss Factor

The blade tip loss factor (B) is no longer input, but is now calculated from the expression below:

$$B = 1 - \frac{\sqrt{2C_T}}{b}$$

3.2 Lock Number

The Lock number at sea-level, ISA conditions ($\gamma_{SL,ISA}$) is now input and the program calculates the Lock number for the given atmospheric condition (γ) from the expression below:

$$\gamma = \gamma_{SL,\ ISA}\left(\frac{\rho}{\rho_{SL,ISA}}\right)$$

3.3 Atmospheric Conditions

As described in Reference 4, atmospheric conditions were found from the program 'ATMOS', the relevant density being then input to POLAR. The program POLAR2 now includes 'ATMOS' as a subroutine to calculate density and the speed of sound for the given conditions and for a variety of Standard Atmospheres.

3.4 Stall Power

Previously, when using POLAR, the stall power was calculated by hand as described in Reference 4. Program POLAR2 now calculates stall power using the following expression

$$P_{stall} = P_o \left(\frac{\alpha_{(1,270)} - 12^\circ}{4^\circ}\right)$$

$$\text{for } 12^\circ < \alpha_{(1,270)} < 16^\circ$$

3.5 Induced Velocity Factor

The effect of non-uniform inflow is to increase the induced power above the value given by momentum theory for uniform inflow. This effect is usually accounted for by applying an induced velocity factor, k_{ind}, to the momentum value of induced velocity.

The program POLAR2 has provision to input an appropriate value pertaining to hover conditions, k_h. For the range of forward flight k_{ind} is calculated by POLAR2 from the relation

(6)

$$k_{ind} = 1 - \frac{k_h - 1}{0.14} (\mu - 0.14)$$

and

$$k_{ind} = 1.0 \text{ for } \mu \geq 0.14$$

Reference 5 (p31) presents curves derived from vortex theory which show the dependence of k_{ind} on thrust coefficient, number of blades and blade twist. For the UH-1H case a value of 1.10 would be applicable which is considerably lower than the value of 1.22 found to be necessary to give agreement with flight results. However this k_{ind} value of 1.22 also includes the influence of downwash impinging on the aircraft fuselage. Flemming and Erikson(6) have shown for the RSRA, where direct measurement of thrust is possible, that the download is approximately 4% of the AUW when OGE. They also showed that, for the IGE case as the aircraft approaches the ground, the download decreases and eventually becomes an upload. In the absence of any data on the down loads for the UH-1H these effects will be absorbed in the induced velocity factor. If, on the other hand, downloads were separately accounted for by increasing the effective AUW, a value of about 1.16 for k_{ind} would be appropriate.

Whilst POLAR2 has no facility for inputting the download as a percentage of AUW, if required the AUW can be suitably adjusted and input in the normal manner, provided k_{ind} is adjusted.

3.6 Tail Rotor, Transmission and Accessories

An estimate of the percentage power absorbed by the combination tail rotor, transmission and accessories is now input to POLAR2 so that the helicopter total power is now output. Alternatively for the special case of a hovering helicopter the tail rotor may be treated also as a separate rotor of sufficient thrust (AUW) to provide the necessary anti-torque moment. This assumes that there is no main rotor - tail rotor - fuselage interactions which in certain cases may give rise to large side-forces on the tail boom (Reference 8). Program POLAR2 first calculates the power required by the main rotor, P_{MR}. The main rotor torque is given by

$$Q_{MR} = P_{MR}/\Omega$$

The distance between the main rotor and tail rotor hubs, l_{TR}, is input so that the anti-torque thrust can be calculated from

$$(T_{TR})_{NET} = Q_{MR}/l_{TR}$$

The tail rotor thrust will be greater than the anti-torque thrust because of the deleterious influence of the tail fin. Reference 5 gives a fin blockage factor (F_{blk}), dependent on tail assembly geometry and configuration, which is input to POLAR2 to calculate tail rotor thrust

$$T_{TR} = F_{blk}(T_{TR})_{NET}$$

The tail rotor power is then calculated by POLAR2, treating it as a separate rotor supporting an all-up weight of T_{TR}.

Finally in the hover case, additional factors must be allowed for auxiliary power losses arising from transmissions and accessories. Reference 5 suggests values of 2% for each, giving a combined 4% for auxiliary power losses.

An example of running POLAR2 on the new ELXSI 6400 computer at ARL is given in the Appendix.

4. RESULTS

4.1 Comparison of POLAR2 with ARDU flight data in hover

4.1.1 OGE Case

Using POLAR2, the agreement between flight data and predicted values shown in Figure 5 is seen to be very good. Points on this curve represent calculations for the wide range of conditions experienced during flight trials, as shown in Table 2.

TABLE 2

Atmospheric conditions at various flight test locations (Ref. 1)

Location	Start Date	Average Pressure Altitude	Average Ambient Temperature	Average Density Altitude
Laverton	3 SEP 73	Sea Level	7°C	-1,000 ft
Lae	4 OCT 73	Sea Level	24°C	1,000 ft
Mt Hagen	23 OCT 73	5350 ft	16°C	6,800 ft
Tambul	28 OCT 73	7300 ft	13°C	9,000 ft
Mt Giluwe	30 OCT 73	10,000 ft	12°C	12,000 ft

The calculated values are also given in Table 3 where the individual contributions to the overall power coefficients are listed. For the worst case compressibility losses represent about 5% of the total power.

TABLE 3

Estimated power components for various atmospheric conditions

All Up Weight (lb)	Atmospheric Conditions	Thrust Coefficient $C_T x10^4$	Tip Mach Number M_T	Power Coefficients ($x10^5$) C_{P_c}	C_{P_o}	C_{P_i}	$C_{P_{TR}}$	$C_{P_{acc}}$	C_P	Total Power HP
7500	Sea Level OAT 24°C	28.7	0.698	0.0	5.9	13.3	1.7	0.9	21.7	817
8500	Sea Level OAT 24°C	32.5	0.698	0.0	6.2	16.0	2.0	1.0	25.2	948
7500	5350ft OAT 16°C	34.0	0.708	0.0	6.3	17.1	2.2	1.1	26.7	848
9500	Sea Level OAT 24°C	36.3	0.698	0.2	6.5	18.9	2.6	1.2	29.4	1106
8500	5350ft OAT 16°C	38.5	0.708	1.0	6.7	20.6	2.9	1.4	32.6	1035
7500	10000ft OAT 12°C	40.0	0.713	1.7	6.9	21.8	3.2	1.4	35.0	944

For a given C_T/σ the compressibility increment depends only on M_{tip} which, for a constant rotor speed, depends on OAT. It follows then that the plotting of C_P vs C_T should not be expected to correlate all data. This was illustrated earlier in Figure 4 where it is shown that at low temperatures there is some compressibility loss even at low C_T, typically at sea level. Thus it would appear that some of the experimental scatter observed in the flight results could arise from a varying presence of compressibility caused by OAT variation.

Increases in the tip Mach number also result directly from operating with a higher rotor speed, as shown in Figure 6. Here the flight data for N2 = 6600 rpm (rotor rpm = 325) show increasing divergence from corresponding data for N2 = 6400 as the thrust coefficient is raised. At the same time estimates given by POLAR2 at typical flight conditions suggest that the compressibility increments are slightly higher in this case when compared with the flight data fairing curve for 6600N2 rpm.

4.1.2. IGE Case

Ground effect is usually explained in terms of the reduction in rotor inflow, ν, caused by the presence of the ground. Hence for a given induced power, $T\nu$, a greater thrust is achieved in ground effect i.e. $(T\nu)_{IGE}=(T\nu)_{OGE}$. It follows conversely that for a given AUW (thrust) the IGE power is less than the OGE value. In the present calculations, it is assumed that the IGE power, for a given AUW and Z/R (rotor height/rotor radius) may be deduced by calculating the OGE power for a reduced equivalent AUW such that

$$\frac{(AUW)_{IGE}}{(AUW)_{OGE}} = \frac{T_{\nu}}{T} = f(Z/R)$$

where f(Z/R) is a ground effect function.

Taking a value of Z/R corresponding to hovering at 3ft skid height, comparison of OGE and IGE flight data at the lower thrust coefficients gives a value for f(Z/R) = 1.17, which agrees with Figures 5-14 of Reference 9. POLAR2 has been run for various atmospheric conditions using the equivalent all up weights for OGE conditions given by

$$(AUW)_{OGE} = (AUW)_{IGE}/1.17$$

Using the value of 1.22 for k_{ind}, the results are compared with flight data in Figure 7.

Generally, agreement is good, but at higher values of C_T when compressibility is present the calculated power tends to be slightly high. This suggests that the calculated compressibility power increment even at the reduced equivalent AUW as described above, is greater than that occurring in the IGE flight condition. This may be explained by referring to Figure 5-10 of Reference 9, where the presence of the ground is shown to reduce the average induced velocity but simultaneously brings about a readjustment of its radial distribution. The inflow is reduced below the mean value towards the centre of the rotor disk but increases above the mean towards the blade tips. Thus in this tip region, the higher-than-otherwise inflow results in smaller angles of attack and hence reduced compressibility (Mach number) effects.

4.2 Out of Ground Effect Hover Margins

To give a further example of the improved capability of POLAR2 we take the case of OGE hover margin prediction. In the practical case the pilot notes the power, i.e. torquemeter* reading in psi, to maintain IGE hover. Reference to a torque margin chart or table gives the extra torque needed for OGE hover, from which the pilot can assess the ability

---

* Maximum allowable torquemeter reading is transmission limited to a value of 50 psi.

of the aircraft to perform safely such a manoeuvre. One form of presentation has been used in Reference 3 from which a curve applicable to an AUW of 8000 lb has been drawn in Figure 8.

The basis of this curve may be traced via the ARDU flight calculator back to the flight data of References 1 and 2. Thus the torque margins are directly related to the difference in OGE and IGE power coefficients as given by the mean curves of Figures 1 a,b. It so happens that the flight data for the higher thrusts were obtained at higher altitude where the OAT averaged ISA+17°C in some cases. In view of the dependence of C_p on temperature (effectively M_{tip}) shown earlier in Figure 4, the mean curve of Figure 1a will indicate a lower power at the higher C_T than might be expected under ISA conditions. On the other hand IGE values are comparatively uninfluenced by compressibility effects. Thus OGE hover margins presented in Reference 3 may be unduly optimistic from the pilot's viewpoint.

Therefore in Figure 8 we note that the thrust margins calculated by POLAR2 for ISA conditions are about 1 psi greater at the higher altitudes. Also shown for comparison is the result given by POLAR[4] where the effect of neglecting compressibility is to seriously underestimate the OGE hover margins at high altitude.

5. CONCLUDING REMARKS

1. The effects of compressibility should be recognised as having a significant influence on the hover performance of the UH-1H Iroquois.

2. The inclusion of a compressibility power expression into the program POLAR2, results in good agreement with UH-1H hover flight data over a wide range of operating conditions.

3. In Service use, the OGE hover margins for the UH-1H, are found using the ARDU calculator, which is based on mean curves fitted to data over a wide range of atmospheric conditions. Since the tip Mach number,

and hence compressibility effects are temperature dependent, these margins may not be sufficient when operating at low temperatures, particularly at high altitudes and all up weights.

4. POLAR2 includes the following features which make it more convenient to use:

a. Variables such as tip loss, atmospheric density and Lock number are calculated within the program rather than being separately input. Likewise the stall power correction is now made by the program.

b. For the hover case, tail rotor performance is calculated along with the main rotor rather than being the subject of a repeat run of the program.

5. An empirical value of induced velocity factor has to be chosen to match flight measurements, as current calculation techniques are not sufficiently well developed. Various influences on the appropriate choice have been discussed.

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APPENDIX

An example is given below of running 'POLAR2' on the new ELXSI 6400 computer at ARL, for the case of the UH-1H Iroquois at hover.

The data required are essentially the same as for 'POLAR'[4], but with additional inputs relating to atmospheric conditions, tail-rotor geometry and various loss factors. These include induced velocity factors for both rotors, tail-fin blockage and auxiliaries.

The auxiliary power loss, i.e. transmission and accessories, is assumed to be 4% of the total power required, which is usual practice.

As stated in Section 2, Ref. 5 gives induced velocity factors which are derived from vortex theory, but as far as is known, have not been validated. Since no other information is available, the value of 1.40 suggested by Ref. 5 for the tail-rotor has been taken. Aerofoil profile drag data for a NACA 0015 (Iroquois tail-rotor) have been analyzed and fitted by a quadratic expression whose coefficients are:

$$\delta_0 = 0.0093, \quad \delta_1 -0.009, \quad \delta_2 = 0.294.$$

Because of Reynolds Number effects on the tail-rotor, it is suggested in Ref. 5 that δ_0 should be increased by 0.0027. Thus the tail rotor profile drag data are taken to be

$$\delta_0 = 0.012$$

$$\delta_1 = -0.009$$

$$\delta_2 = 0.294$$

A. INPUT DATA (see Ref. 4 for 'ATMOS' details)

```
:
:POLAR2
 TITLE (TWO LINES OF UP TO 60 CHARACTERS)
 :   POLAR2 - Iroquois Hover OGE
 :   7500lb at 10000ft, OAT 12C
 SET ATMOSPHERIC FLAG, KEYAIR (1,2,3,4,5 OR 6): 3          'ATMOS'
 STATE PRESSURE ALTITUDE (IN FEET): 10000
 AIRFIELD REFERENCE TEMPERATURE, TDAY (IN DEG. C): 12      input
 QNH OF THE DAY (IN MILLIBARS): 1013.25
 HEIGHT OF THE AIRFIELD REFERENCE POINT, HAFR: 10000
 ARE UNITS IN IMPERIAL OR METRIC (I OR M) ? I
 ALL UP WEIGHT (N OR LB) = ? 7500
 EQUIVALENT FLAT PLATE AREA (M**2 OR FT**2) = ? 22.5

 main rotor data :
 ROTOR TIP SPEED (M/S OR FT/S) = ? 791.7
 ROTOR RADIUS (M OR FT) = ? 24
 ROTOR BLADE CHORD (M OR FT) = ? 1.75
 NUMBER OF ROTOR BLADES = ? 2
 2D LIFT CURVE SLOPE (/RAD) = ? 5.73
 INDUCED VELOCITY FACTOR(in hover) = ? 1.22
 BLADE TWIST (DEG) = ? -10
 LOCK NUMBER (ISA,sea level) = ? 7
 DRAG POLAR CO-EFFICIENT (DEL0) = ? 0.0084
 DELTA1 (/RAD) = ? -0.0102
 DELTA2 (/RAD**2) = ? 0.384
 AUXILIARY POWER LOSS (as % of total power) = ? 4.0
 IS RANGE/ENDURANCE REQUIRED ? (Y OR N) : N
 IS A SPEED-POWER POLAR REQUIRED ? (Y OR N) : N
 IS HELICOPTER HOVERING (Y OR N) ? Y

 tail rotor data :
 ROTOR TIP SPEED (M/S OR FT/S) = ? 715.7
 ROTOR RADIUS (M OR FT) = ? 4.25
 ROTOR BLADE CHORD (M OR FT) = ? 0.7
 NUMBER OF ROTOR BLADES = ? 2
 2D LIFT CURVE SLOPE (/RAD) = ? 5.73
 INDUCED VELOCITY FACTOR(in hover) = ? 1.40
 BLADE TWIST (DEG) = ? 0
 LOCK NUMBER (ISA,sea level) = ? 2
 DRAG POLAR CO-EFFICIENT (DEL0) = ? 0.012
 DELTA1 (/RAD) = ? -0.009
 DELTA2 (/RAD**2) = ? 0.294
 TAIL ROTOR MOMENT ARM (M OR FT) = ? 28.79
 FIN BLOCKAGE FACTOR = ? 1.11

:
```

B. 'POLAR2' Output

```
:LIST POLAR2.OUT
  POLAR2 - Iroquois Hover OGE
  7500lb at 10000ft, OAT 12C

 atmospheric conditions :
 ATMOSPHERIC FLAG = 3
 AIRFIELD REFERENCE ALTITUDE =  10000.0 ft
 PRESSURE ALTITUDE =  10000.0 ft
 AIRFIELD REFERENCE TEMPERATURE =  12.0 Celsius
 AMBIENT TEMPERATURE =  285.15 Kelvin
 QNH = 1013.25 mb
 AMBIENT PRESSURE =  1455.33 lbs/ft**2
 AIR DENSITY =  .0016518 slug/ft**3
 SPEED OF SOUND =  1110.6 ft/s

 aircraft data :
 ALL UP WEIGHT =      7500.0 lbs
 EQUIVALENT FLAT PLATE AREA =  22.5 ft**2
 AIRSPEED =       .00 knots
 AUXILIARY POWER LOSS (as % of total power) =  4.0 %

 main rotor data :
 NUMBER OF ROTOR BLADES =  2.0
 ROTOR TIP SPEED =  791.7 ft/s
 ROTOR RADIUS =  24.0 ft
 ROTOR BLADE CHORD =  1.8 ft
 ROTOR BLADE TWIST =  -10.0 deg
 2D LIFT CURVE SLOPE =  5.73
 DRAG POLAR COEFFICIENT (DELTA 0) =   .0084
 DELTA 1 =  -.0102 /rad
 DELTA 2 =   .3840 /rad**2
 LOCK NUMBER (ISA,sea level) =   7.0


 LOCK NUMBER =  4.86
 INDUCED VELOCITY FACTOR (in hover) =  1.22
 INDUCED VELOCITY FACTOR =  1.22
 TIP LOSS FACTOR =    .96
 ADVANCING TIP MACH NUMBER =    .71
 ADVANCE RATIO (MU) =    .000
 INDUCED VELOCITY (NU) =  43.21 ft/s
 INFLOW RATIO (LAMBDA) =   -.0546
 FLAT PLATE DRAG =      .0 lbs
 THRUST =   7500.0 lbs
 THRUST COEFFICIENT =   .00400
 ROTOR SOLIDITY =   .0464
 COLLECTIVE (THETA 0) =  18.0 Deg
 CONING ANGLE (a0) =   3.0 Deg
 LONGITUDINAL FLAPPING ANGLE (a1) =    .0 Deg
 LATERAL FLAPPING ANGLE (b1) =    .0 Deg
 DISC ANGLE OF ATTACK =    .0 Deg
 RETREATING BLADE TIP ANGLE OF ATTACK =   4.9 Deg
 INDUCED POWER =   589.3 Hp
 PARASITE POWER =      .0 Hp
 PROFILE POWER =   182.0 Hp
 COMPRESSIBILITY POWER =    51.7 Hp
 STALL POWER =      .0 Hp
 TOTAL POWER =   823.0 Hp
 REQUIRED/AVAILABLE SHAFT POWER =   823.0 Hp
 CLIMB POWER =      .0 Hp
 RATE OF CLIMB =      .0 ft/min
 CLIMB ANGLE =     .0 Deg

 tail rotor data :
 TAIL ROTOR MOMENT ARM =  28.79 ft
 FIN BLOCKAGE FACTOR =  1.11
 NUMBER OF ROTOR BLADES =  2.0
 ROTOR TIP SPEED =  715.7 ft/s
 ROTOR RADIUS =   4.3 ft
 ROTOR BLADE CHORD =    .7 ft
 ROTOR BLADE TWIST =     .0 deg
 2D LIFT CURVE SLOPE =  5.73
```

```
DRAG POLAR COEFFICIENT (DELTA 0) =    .0120
DELTA 1 =  -.0090 /rad
DELTA 2 =   .2940 /rad**2
LOCK NUMBER (ISA,sea level) =   2.0

LOCK NUMBER =  1.39
INDUCED VELOCITY FACTOR (in hover) =  1.40
INDUCED VELOCITY FACTOR =  1.40
TIP LOSS FACTOR =    .93
ADVANCING TIP MACH NUMBER =    .64
ADVANCE RATIO (MU) =    .000
INDUCED VELOCITY (NU) =  74.41 ft/s
INFLOW RATIO (LAMBDA) =   -.1040
FLAT PLATE DRAG =        .0 lbs
THRUST =     529.5 lbs
THRUST COEFFICIENT =    .01103
ROTOR SOLIDITY =    .1049
COLLECTIVE (THETA 0) =  17.4 Deg
CONING ANGLE (a0) =    1.1 Deg
LONGITUDINAL FLAPPING ANGLE (a1) =    .0 Deg
LATERAL FLAPPING ANGLE (b1) =    .0 Deg
DISC ANGLE OF ATTACK =    .0 Deg
RETREATING BLADE TIP ANGLE OF ATTACK =  11.5 Deg
INDUCED POWER =    71.6 Hp
PARASITE POWER =       .0 Hp
PROFILE POWER =    16.0 Hp
COMPRESSIBILITY POWER =       .0 Hp
STALL POWER =      .0 Hp
TOTAL POWER =    87.7 Hp
REQUIRED/AVAILABLE SHAFT POWER =    87.7 Hp
CLIMB POWER =      .0 Hp
RATE OF CLIMB =      .0 ft/min
CLIMB ANGLE =    .0 Deg

TOTAL ROTOR POWER =    910.7 Hp
TOTAL HELICOPTER POWER =    948.6 Hp
TOTAL HELICOPTER POWER COEFFICIENT =  35.27E-05

CPUTIME =    .196 seconds
:
```

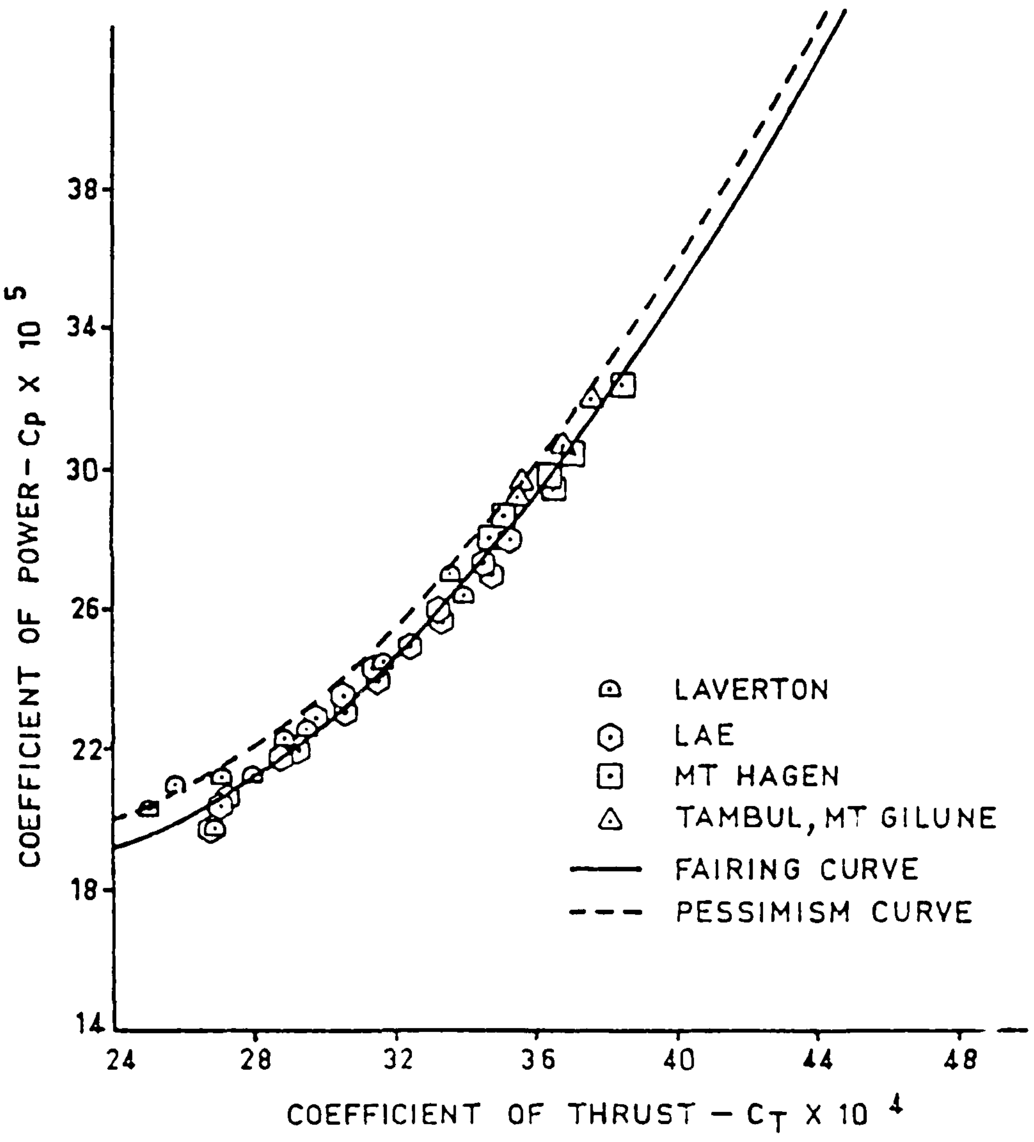


FIG. 1a POWER REQUIRED TO HOVER OGE, N2 [illegible]
(ARDU FLIGHT DATA REPRODUCED FROM Ref. [illegible])

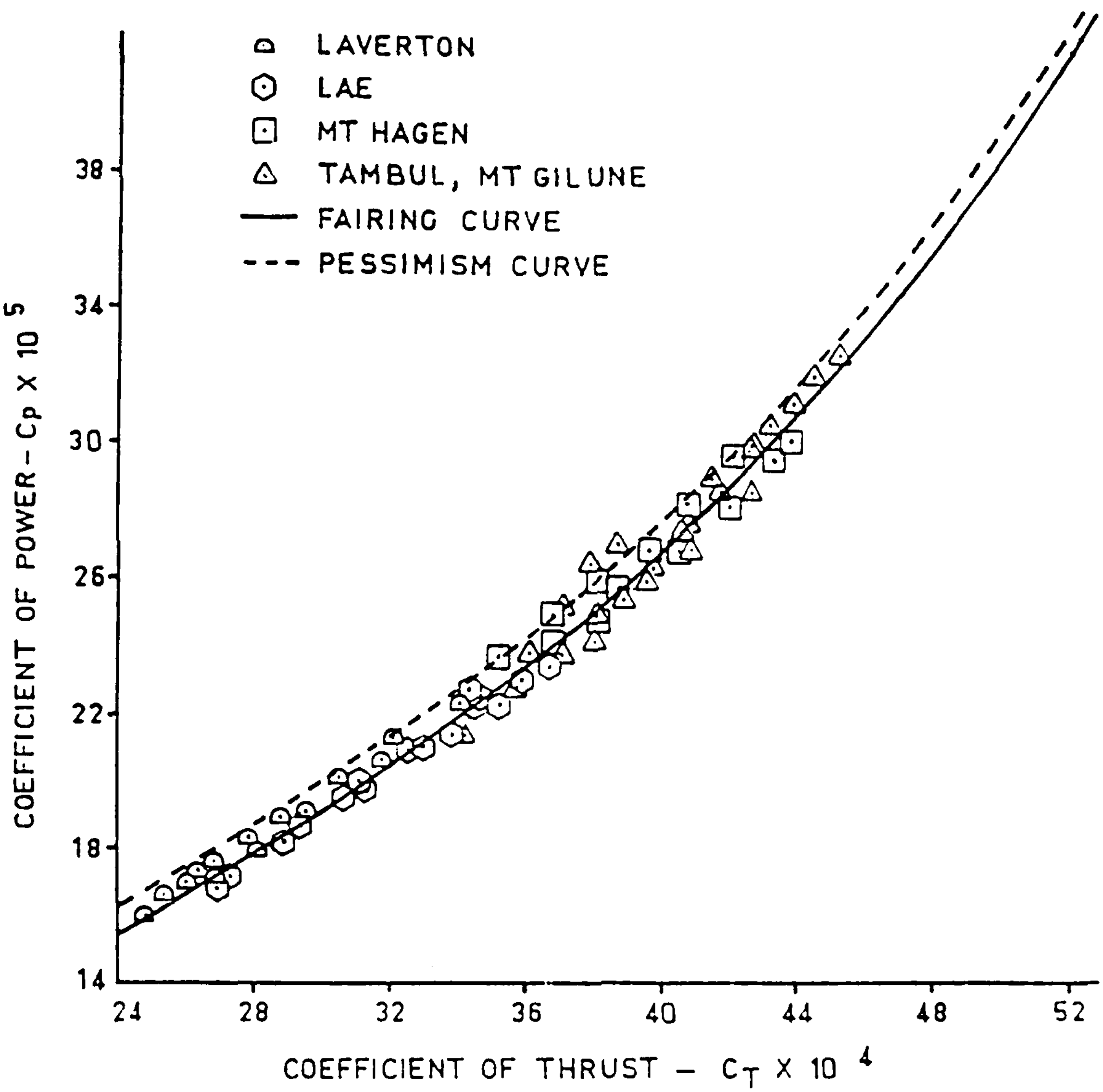


FIG. 1[illegible] POWER REQUIRED TO HOVER IGE, N[illegible] = [illegible] rpm
(ARDU FLIGHT DATA REPRODUCED FROM Ref. 1)

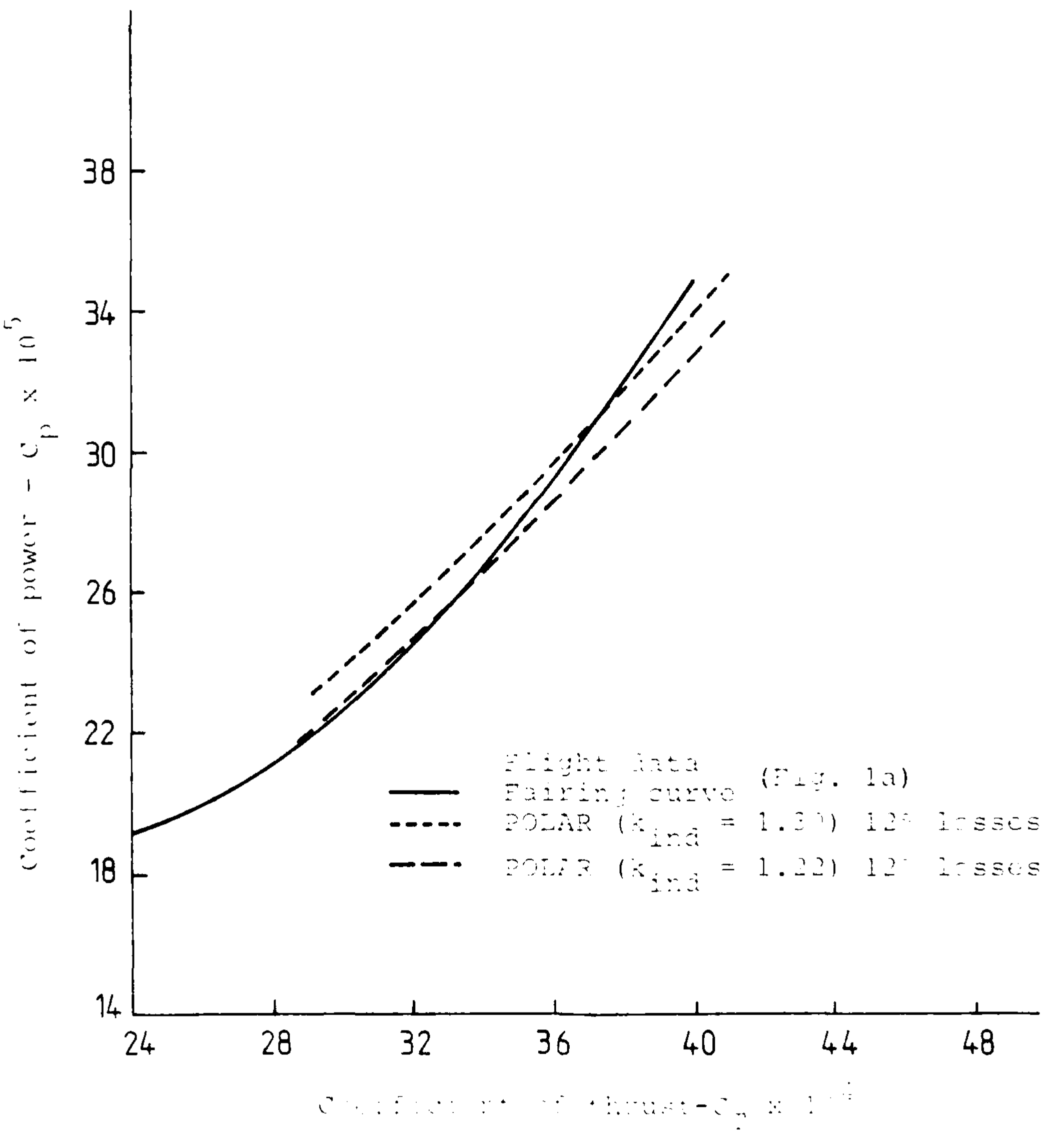


FIG. 2 COMPARISON OF FAIRING CURVE FOR OGE HOVER, N2 = 64[illegible] rpm WITH PREDICTIONS OF POLAR WITH VARYING k_{ind}

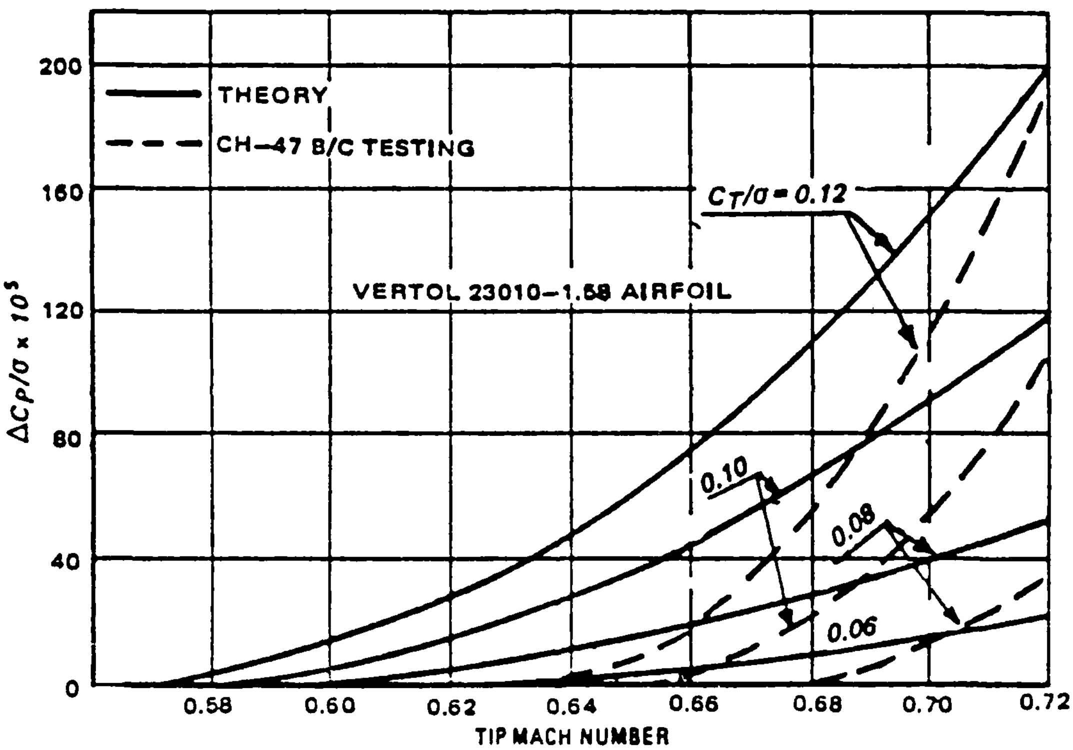


FIG. 3a COMPRESSIBILITY POWER INCREMENT AS A FUNCTION OF TIP MACH NUMBER AND C_T/σ (from Ref. 5)

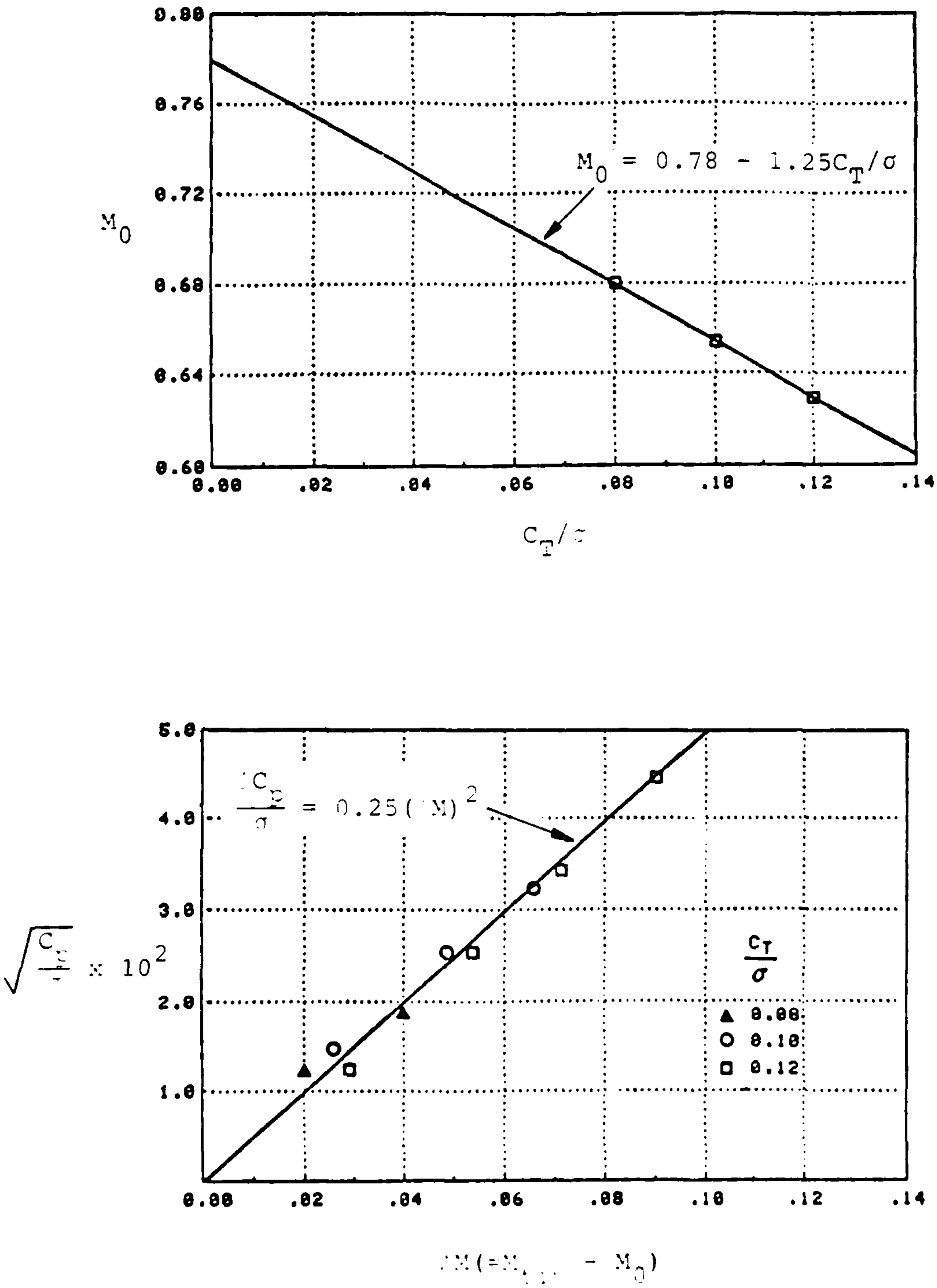


FIG. 3b EXPRESSIONS USED BY POLAR2 TO DESCRIBE COMPRESSIBILITY INCREMENTS OF FIG. 3a

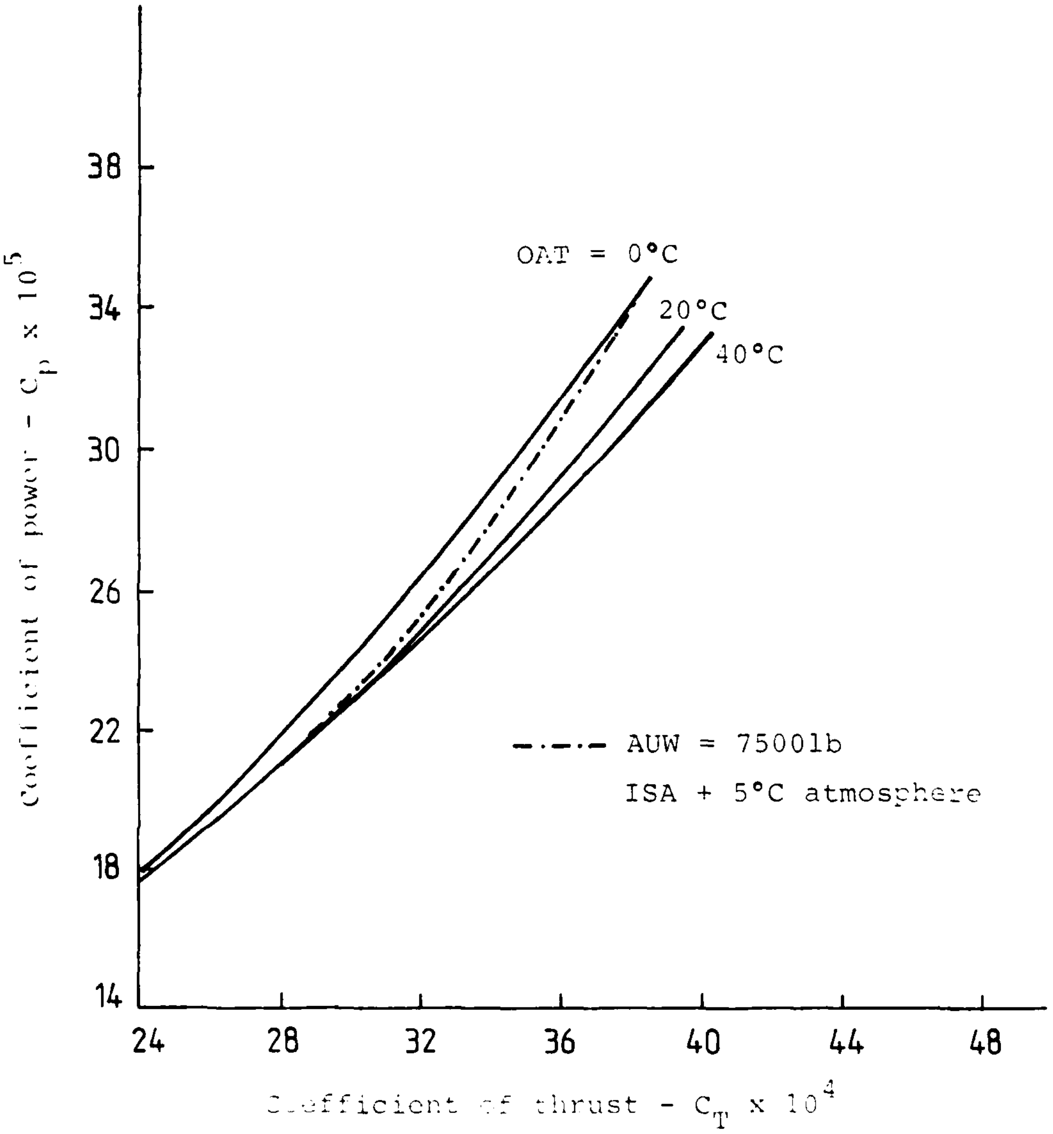


FIG. 4 VARIATION OF PREDICTED POWER WITH AIR TEMPERATURE FOR CONSTANT TIP SPEED (N2 = 6400 rpm, OGE)

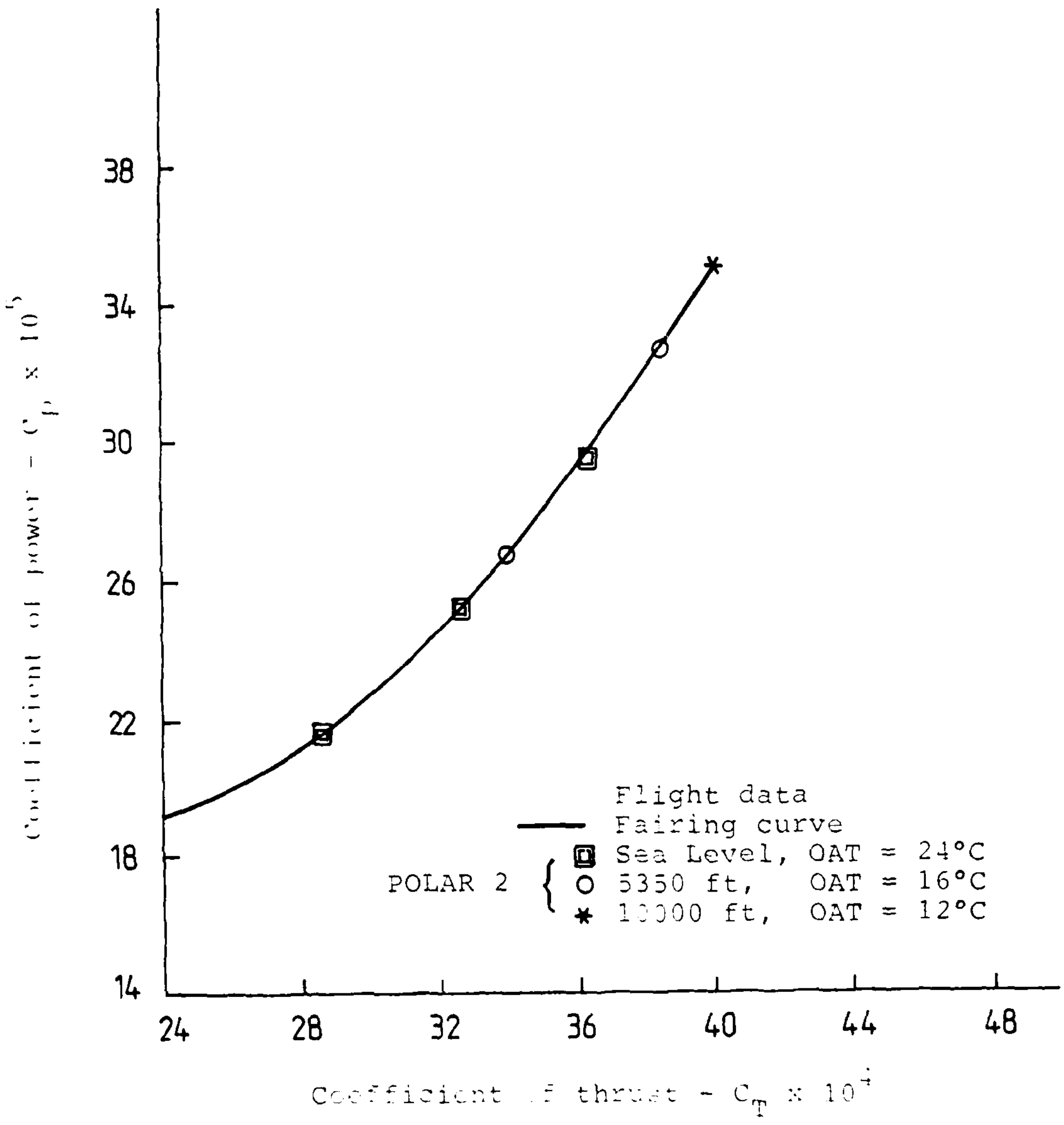


FIG. 5 COMPARISON OF FAIRING CURVE (FIG. 1a) WITH POLAR 2 PREDICTIONS, OGE, N2 = 6400 rpm

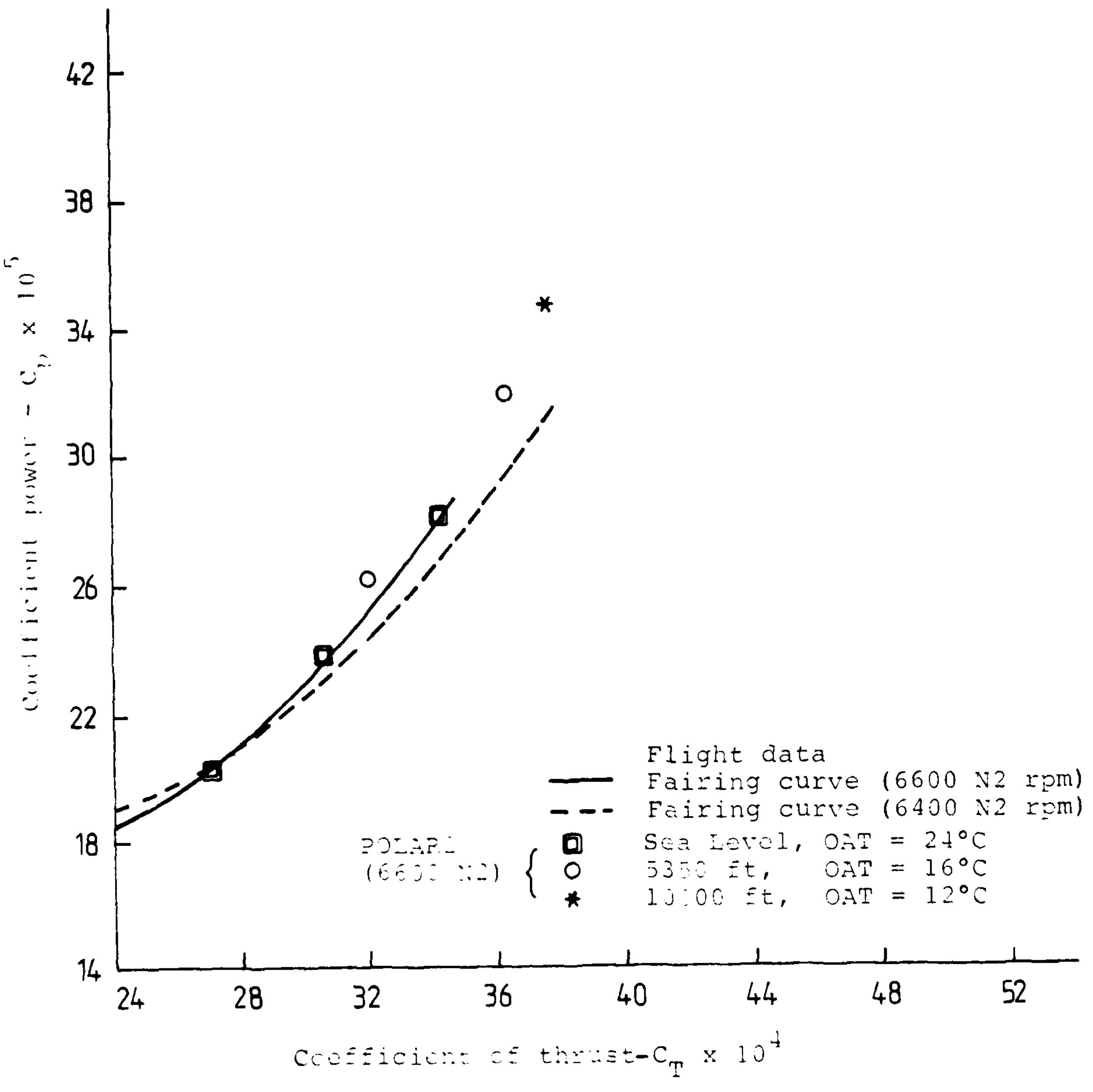


FIG. 6 EFFECT OF HIGHER TIP SPEED ON OGE POWER LOSS
COMPARISON WITH POLAR 2

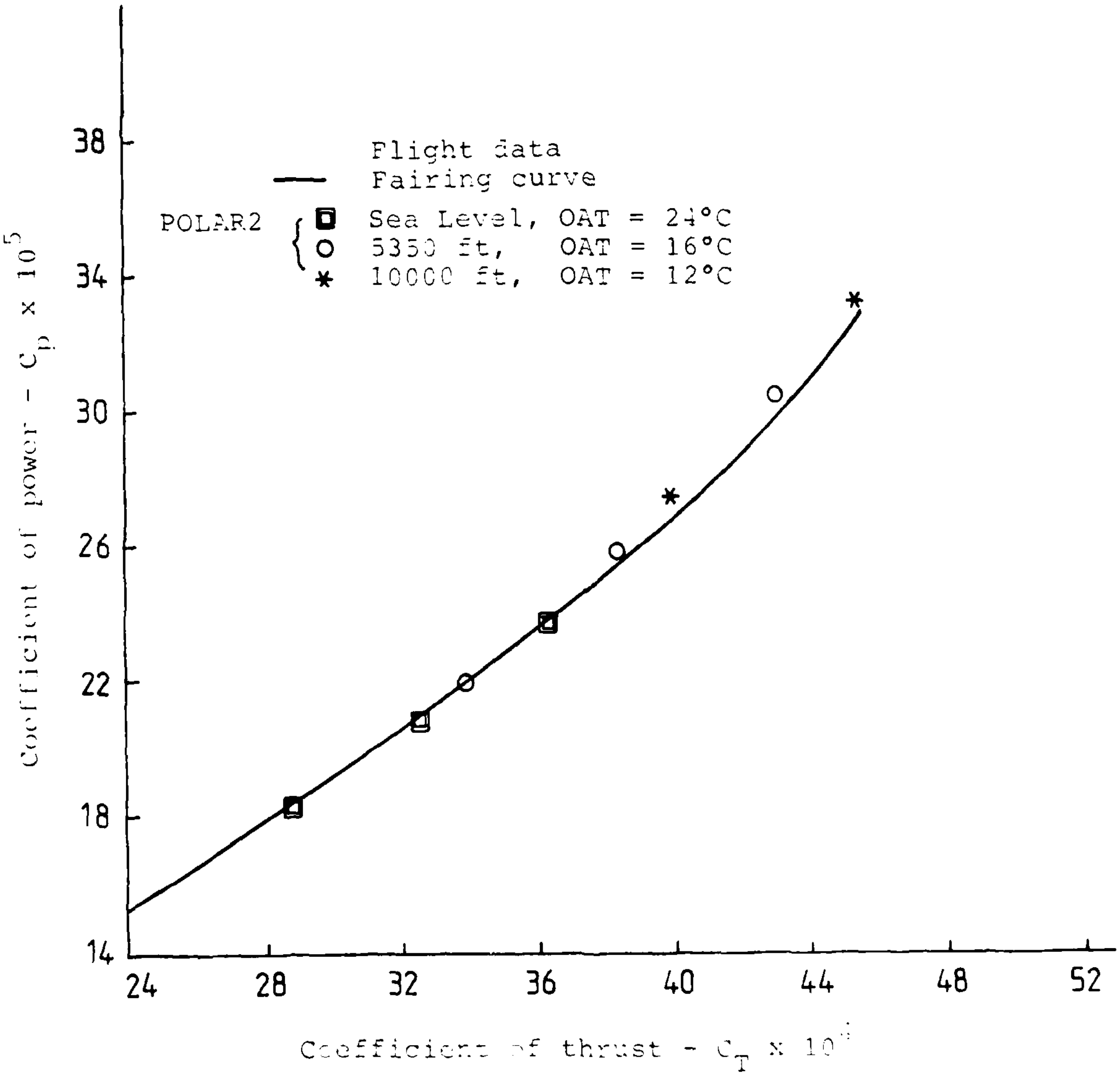
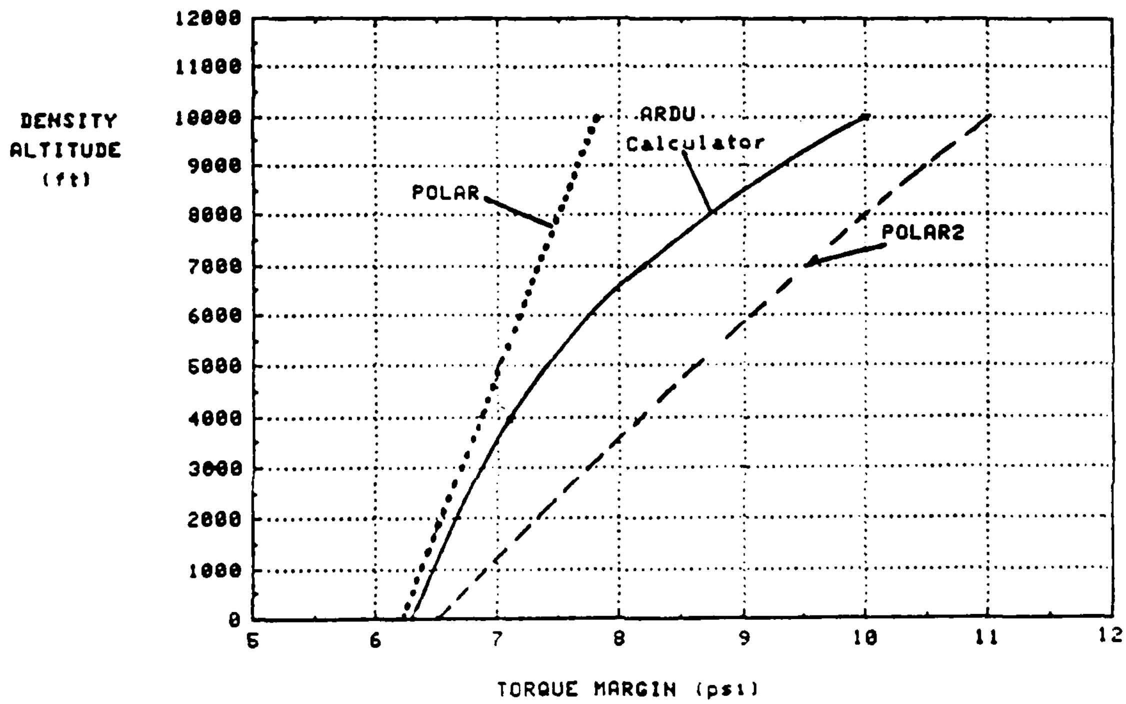


FIG. 7 COMPARISON OF FAIRING CURVE (FIG. 11) WITH POLAR 2 PREDICTIONS, IGE, N2 = [illegible] rpm



$$\text{Torque(psi)} = \frac{5252 \times SHP \times DPTV}{1125 \times N2}$$

FIG. 8 COMPARISON OF OGH HOVER TORQUE MARGINS FOUND USING ARDU CALCULATOR (REF. 3) WITH THOSE FOUND USING POLAR AND POLAR2 FOR ISA CONDITIONS. AUW [illegible]LB

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14. Descriptions

Hovering
Helicopter performance
POLAR2 (computer program)

15. COSATI Group

01010

16. Abstract
The hover performance of the UH-1H Iroquois has been estimated under a variety of operational conditions using POLAR2, a program based on blade element theory. This program is an improved version of POLAR, a program previously developed at ARL, which did not allow for compressibility effects. The occurrence of these effects in a hovering situation is discussed, and a relationship allowing for such effects has been derived and included in POLAR2. Other improvements, designed to make the program more convenient to use include the calculation of tail rotor performance together with variables such as tip loss, air density and Lock number which were previously input. The role of the induced velocity factor is also discussed. Finally, comparisons of estimates using POLAR2 and ARDU flight trials data for the UH-1H are presented.

PF 65

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